Plans for Simulation and Validation in the US Tokamak Research Program

US Tokamak Research Program

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E-TASC Meeting
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Theory and Modeling in the US

Theory and Modeling in the US Program

Program	Primary Purpose
Base Theory / University Grants	Foundational Research
SciDAC	HPC & Integrated Modeling
FIRE	Technology Development (~15% ModSim)
Genesis	AI / ML (DOE-wide, % for Fusion ModSim TBD)
Tokamak Research (TR)	Control, Experiment Analysis, VVUQ (~20% ModSim)
INFUSE	Voucher program to for industry (~30% ModSim)
Milestone	Reimbursement program for industry (? ModSim)

Theory Programs

Public-Private Partnerships

Foundational: Base Theory and University Grants

- **Base Theory is block funding to theory groups at National Labs and other large institutions**
  - 5-year periods, generally stable from period to period
  - Size varies, but typically only support a few FTEs
  - PPPL, ORNL, LLNL, LANL, GA, MIT, …
  - Have been shrinking relative to other funding sources

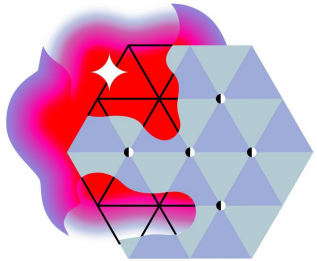
- **Single-PI university grants are typically support one professor and a couple grad students, postdocs, or staff**

SciDAC: Scientific Discovery through Advanced Computing

- **Partnerships between the Advanced Scientific Computing Research (ASCR) and Fusion Energy Science (FES) programs**
  - ~$3M / year for 5 years
- **Historically focused on high-fidelity modeling and high performance computing**
- **Recently, more emphasis on developing frameworks for integrated modeling**

SciDAC Project	Topic
FRONTIERS in Leadership Gyrokinetic Simulation	Core Transport
Surrogate Models for Accurate and Rapid Transport Solutions (SMARTS)	Core Transport
Computational evaluation and design of actuators for Core-Edge Integration (CEDA)	Edge Transport
Developing Multiscale Simulation of Boundary Plasma Dynamics (ABOUND)	Edge Transport
Development of High-Fidelity Simulation Capabilities for ELM-free Design Optimization (CETOP)	ELMs
Center for Advanced Simulation of RF - Plasma - Material Interactions	RF, Materials
Center for Simulation of Plasma - Liquid Metal Interactions in Plasma Facing Components and Breeding Blankets of a Fusion Power Reactor	Liquid Metals, Transients
Fusion REactor Design and Assessment (FREDA)	Tokamak Design
High-Fidelity Simulations for Stellarators (HifiStell)	Stellarators
High-fidelity Digital Models for Fusion Pilot Plant Design (StellFoundry)	Stellarators
Integrated Thermomechanical Model of First-wall Components Under Evolving Chemistry and Microstructure During Fusion Reactor Operation	Materials
Unlocking kinetic effects in IFE-relevant simulations on Exascale supercomputers	IFE

FIRE: Fusion Innovation Research Engines



- **FIRE collaboratives support technology development and the application of research to "end-user" needs**
  - Have advisory boards that include end-user representatives (industry, ITER, etc.)
  - These are new (started in 2025)
  - Up to $5M / year for 4 years
  - Goal is technology development. A few are focused on modeling.

FIRE Collaboratives
Advanced Profile Prediction for Fusion Pilot Plant Design (APP - FPP) [D. Ernst, MIT]
Mitigating Risks from Abrupt Confinement Loss (MiRACL) [N. Ferraro, PPPL]
Fusion Energy Data Ecosystem and Repository (FEDER) [R. Nazikian, GA]
Fuel Cycle FIRE Collaborative (FC-FIRE)
Accelerating Fusion Blanket Development through Nuclear Testing (BNT)
Target Injector Nexus for Experimental Development (TINEX)
Rapid high-fidelity bulk irradiated materials data generation to accelerate solutions for commercial fusion energy systems
The Fusion Innovation Research Engine Integrated Materials Program to Accelerate Chamber Technologies (FIRE IMPACT)
Fusion Neutrons for Integrated Blanket Technology Development Through Advanced Testing and Design
Neutron-Irradiation-Tolerant REBCO Tapes for Compact Fusion
Solution-Oriented Workflow for Integrated Fusion Technology in Plasma-Facing Components (SWIFT-PFCs)
Advancing the maturity of liquid metal (LM) plasma facing materials and first wall concepts
Blanket Collaborative on Test Facilities

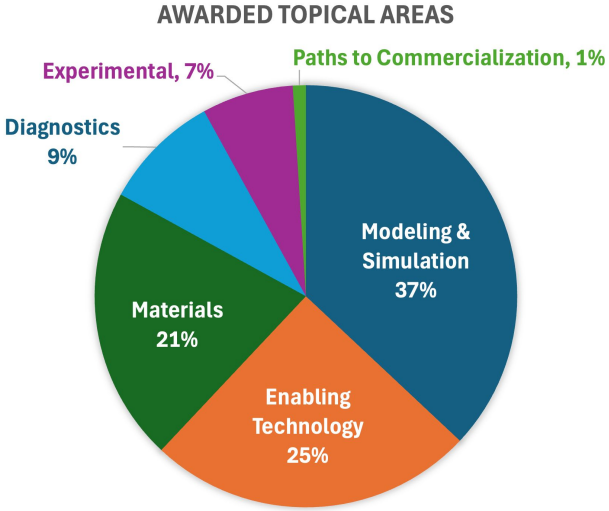
AI in the US Theory and Modeling Program

- **Increasing funding for AI/ML is largely offsetting reductions in base theory**
- **“Genesis Mission” was recently announced as DOE-wide AI initiative. Funding is still unclear.**
- **Will cover Compute, Data, Models, and Applications, and will build on existing initiatives:**
  - “American Science Cloud (AmSC)”: hardware and software infrastructure for AI
  - “Transformational AI Models Consortium (ModCon)”: build and deploy AI models
- **Genesis will include “Lighthouse Challenges” and “Lighthouse Projects”**
  - Challenge: big science / tech problem that AI could help solve
  - Project: a project to address all or part of one of the challenges
  - Fusion might be a “challenge” with one or two “projects” -- stay tuned.

https://genesis.energy.gov

Public-Private Partnership for Theory and Modeling

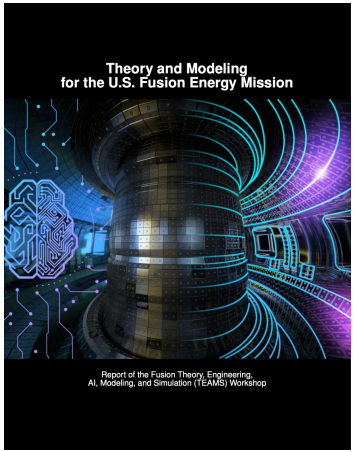
- **INFUSE is a voucher program**
  - Companies submit “Requests for Assistance” (RFA) from National Labs or Universities
  - Up to $500k, usually for one year
  - Work at National Labs / Universities is funded by DOE
  - Companies must contribute at least 20% of the costs (usually in-kind)
  - Modeling & Simulation is the most commonly awarded RFA



- **Milestone reimbursement program**
  - Companies propose milestones to DOE, and DOE reimburses their costs if successful
  - Some ModSim is being done as part of this. Difficult to track because milestones and associated work are not publicly disclosed.

DOE Roadmap and TEAMS Report

- **DOE is developing a Fusion Science & Technology Roadmap**
  - Phase I (Oct. 2025) describes science and technology gaps and near-/mid-/long-term goals
  - Phase II (not yet released) expected to describe detailed metrics and milestones
  - Emphasis on mission-driven metrics, public-private partnerships, and international collaboration
- **Fusion Theory, Engineering, AI, Modeling, and Simulation (TEAMS) Workshop provided input to the Roadmap**
  - Not yet public
  - Describes the critical role of Theory & Modeling in projecting to inaccessible physical regimes (for design and for AI)
  - Identifies cross-cutting and topical priority research opportunities (PROs) for theory and modeling
  - Emphasizes need for foundational theory, systematic VVUQ and data management, and development of qualified tools for design



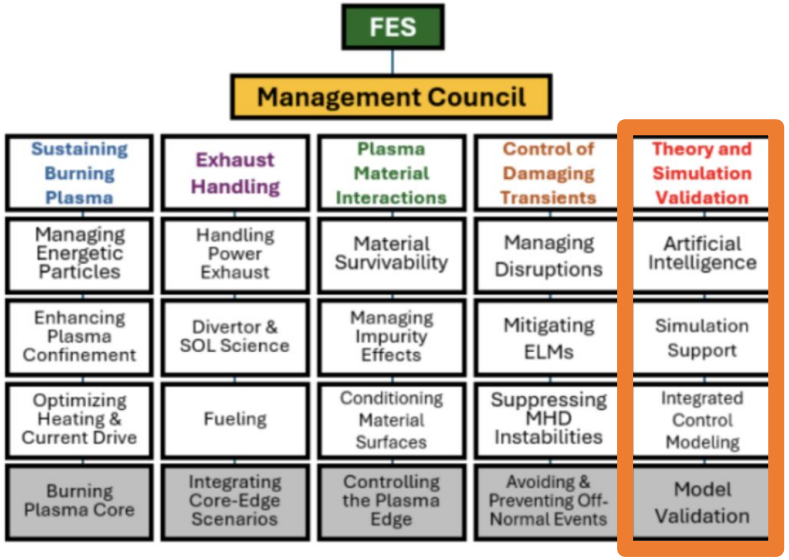
Focus on systematic VVUQ and control qualification

- **Much existing validation is not systematic**
  - Validation datasets often include only a few discharges on one facility
  - Validation of different codes often involves different datasets
  - Workflows are not well documented or reproducible
    - People make individual choices, and may tune these to improve agreement -- no two people get the same result!
- **The lack of systematic validation makes UQ challenging**
  - Insufficient data to quantify uncertainty over a broad range of parameters
  - VVUQ is only meaningful if workflows are reproducible
- **We want to push US program towards systematic VVUQ. This will partnerships both domestic (e.g. SciDACs) and international (e.g. ITPEA)**
  - Multi-facility datasets, reproducible workflows, uncertainty quantification

Theory and Modeling in the TR Program

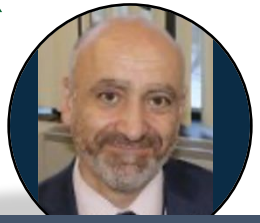
TR Program is a Unified Approach to US Tokamak Research

- **TR program mostly funds experimental research**
  - DIII-D, AUG, KSTAR, TCV, WEST, …
- **Most TR areas include some modeling**
  - Focused on analysis, not development
- **Most US theory and modeling occurs outside of TR program**
  - Coordination and partnerships are required (e.g. TR / SciDAC)
- **Theory, Simulation, and Validation (TSV) is a Major Topical Area**



TSV Topical Area Coordinates AI, Control, & VVUQ in TR

- **Coordination at the MTA level seeks to define data management and VVUQ standards and procedures across the TR program**
- **High level goals:**
  - Validate core-to-wall predictive capabilities, with quantified uncertainty and applicability domains, to enable reactor-regime projections for de-risking FPP/TPP scenarios and design.
  - Develop and qualify AI-enabled plasma control models, with embedded uncertainty and applicability domains, to support the design of fault-tolerant high-performance FPP/TPP operation.
  - Establish extensible, automated workflows, with integrated UQ and data provenance, to accelerate and scale validation cycles for FPP realization.
- **Will utilize existing Fusion Data Platform (FDP) and upcoming FEDER project for federated data access (more details in talk by Sammuli)**



R. Nazikian (GA)

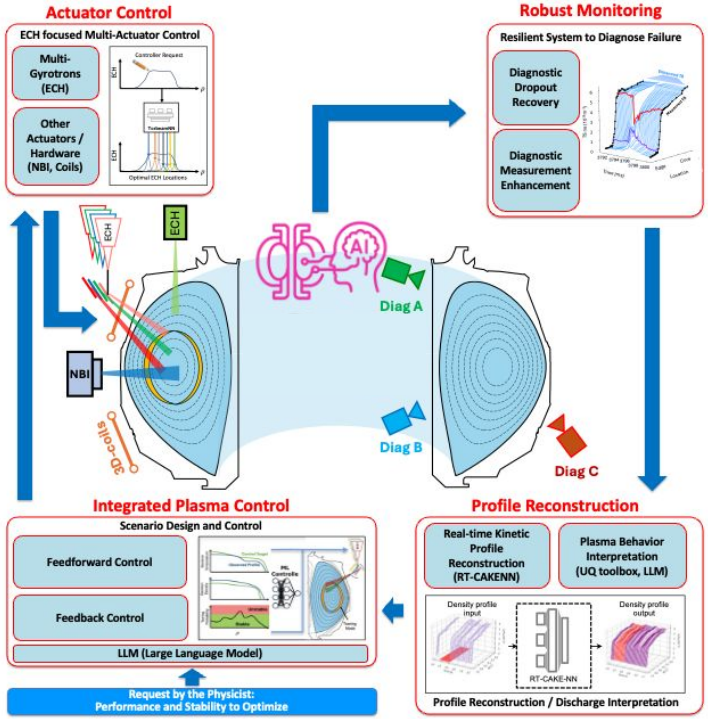
Theory and Simulation Validation

AI/ML & Control

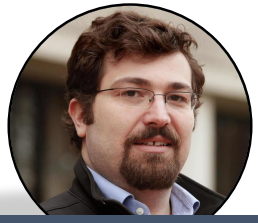
Simulation Support

VVUQ (cross-cut)

AI/ML + Control: fully AI-driven plasma control system enabling robust operation of FPP-relevant scenarios



- **Resilient Monitoring:** Maintain control performance under diagnostic degradation or failure using AI reconstruction.
- **Multi-Actuator Control:** Demonstrate autonomous, reactor-relevant control coordinating multi-ECH, NBI, and magnetic coils
- **End-to-End Optimization:** Integrate AI-driven scenario optimization from ramp-up to ramp-down for full-discharge efficiency



E. Kolemen (PPPL)

Theory and Simulation Validation

AI/ML & Control

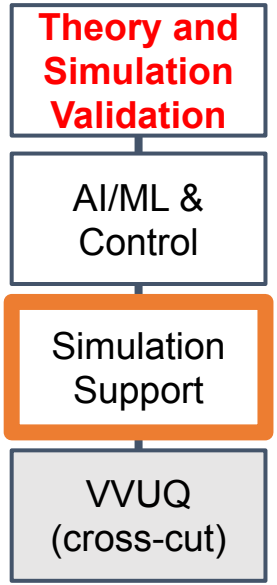
Simulation Support

VVUQ (cross-cut)

Simulation Support: validated, predictive core-to-wall simulations with quantified uncertainty

- **Execute coordinated multi-machine validation to evaluate and refine integrated Core-to-Wall predictions**
  - Build upon and expand ongoing collaborative efforts among DIII-D, KSTAR, and WEST to utilize controlled variation of key physics parameters
- **Quantify uncertainty in Core-to-Wall integrated modeling for FPP design risk reduction**
  - Connect validation efforts to FPP prediction with quantified uncertainties
  - Establish a platform for the iterative reduction of the most critical modeling uncertainties between targeted experiments, multi-machine validation, and component development
- **Shift validation efforts from "improving everything" to "improving what matters most for FPP design decisions**

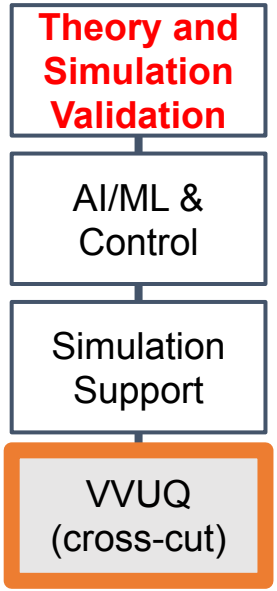
J.M. Park (ORNL)



VVUQ: Integrated physics and advanced data science

- **Research goals:**
  - Predictive confidence-bounded control simulation
  - Integrated physics–ML modeling
  - Robust reactor relevant state estimation and control
  - Support Cross-machine validation and qualification
  - Reproducible, federated data infrastructure
- **Major gaps addressed:**
  - Integration of VVUQ into control design and state estimation, enabling confidence-bounded predictive control validated across DIII-D, KSTAR, and WEST
  - Hybrid physics–ML frameworks within standardized FDP/IRI workflows for cross-facility reproducibility, robust state estimation, and traceable control qualification with uncertainty propagation

H. Anand (GA)



TR / Theory Partnerships are Crucial

- **Most model development and application is funded outside of TR program**
  - Connections are being established between STAs and SciDACs / FIREs
  - TR presence on US Fusion Theory Coordinating Committee (TCC) and theory conferences (e.g. Sherwood)
- **Collaboration with Theory program is necessary and mutually beneficial**
  - TR produces data that can be used by SciDACs / FIREs for validation / analysis
  - TR informs SciDACs / FIREs about critical modeling needs
  - SciDACs / FIREs inform TR about validation needs and new modeling capabilities

TR Simulation and Modeling Summary

- **The new US TR program now includes Theory Simulation and Validation (TSV) Major Topical Area**
  - AI/ML + Control
  - Simulation Support
  - VVUQ
- **We intend to transition to a systematic, multi-facility approach to VVUQ**
- **TR seeks to engage with broader US effort (SciDACs / FIREs) and with the international effort**
- **How can we best collaborate/coordinate with EUROfusion?**
  - Coordinate approach to data access / validation databases